7.0 SITE HYDROLOGY

The hydrologic character of the Nevada Test Site (NTS) and vicinity reflects the region's arid climatic conditions and complex geology (D'Agnese *et al*., 1997). The hydrology of the NTS has been extensively studied for over 40 years (U. S. Department of Energy [DOE] 1996c), and numerous scientific reports and large databases are available. The following sections present an overview of the hydrologic setting of the NTS and vicinity, including summary descriptions of surface water and groundwater, hydrogeologic framework, and finally a summary of the hydrogeology for each of the former underground test areas on the NTS.

7.1 SURFACE WATER

The NTS is located within the Great Basin, a closed hydrographic province which comprises several closed hydrographic basins (Figure 7.1). The closed hydrographic basins of the NTS (most notably Yucca and Frenchman Flats) are subbasins of the Great Basin. Streams in the region are ephemeral, flowing only in response to precipitation events or snowmelt. Runoff is conveyed through normally dry washes toward the lowest areas of the closed hydrographic subbasins, and collects on playas. Two playas (seasonally dry lakes) occur on the NTS: Frenchman Lake and Yucca Lake, which lie in Frenchman and Yucca Flats, respectively. While water may stand on the playas for a few weeks before evaporating, the playas are dry most of the year. Surface water may leave the NTS in only a few places, such as Fortymile Canyon in the southwestern NTS.

Springs that emanate from local perched groundwater systems are the only natural sources of perennial surface water in the region. There are 20 known springs or seeps on the NTS (Hansen *et al*., 1997) (Figure 7.2). Spring discharge rates are low, ranging from 0.014 to 2.2 liters/sec (0.22 to 35 gal/min) (International Technology [IT] 1997). Most water discharged from springs travels only a short distance from the source before evaporating or infiltrating into the ground. The springs are important sources of water for wildlife, but they are too small to be of use as a public water supply source.

Other surface waters on the NTS include man-made impoundments constructed at several locations throughout the NTS to support various operations. These are numerous, and include open industrial reservoirs, containment ponds, and sewage lagoons (DOE 1998a). Surface water is not a source of drinking water on the NTS.

7.2 GROUNDWATER

The NTS is located within the Death Valley regional groundwater flow system, one of the major hydrologic subdivisions of the southern Great Basin (Waddell *et al*., 1984; Laczniak *et al*., 1996). Groundwater in southern Nevada is conveyed within several flow-system subbasins within the Death Valley regional flow system (a subbasin is defined as the area that contributes water to a major surface discharge area [Laczniak, *et al*., 1996]). Three principal groundwater subbasins, named for their down-gradient discharge areas, have been identified within the NTS region: the Ash Meadows, Oasis Valley, and Alkali Flat-Furnace Creek Ranch subbasins (Waddell *et al*., 1984) (Figure 7.3).

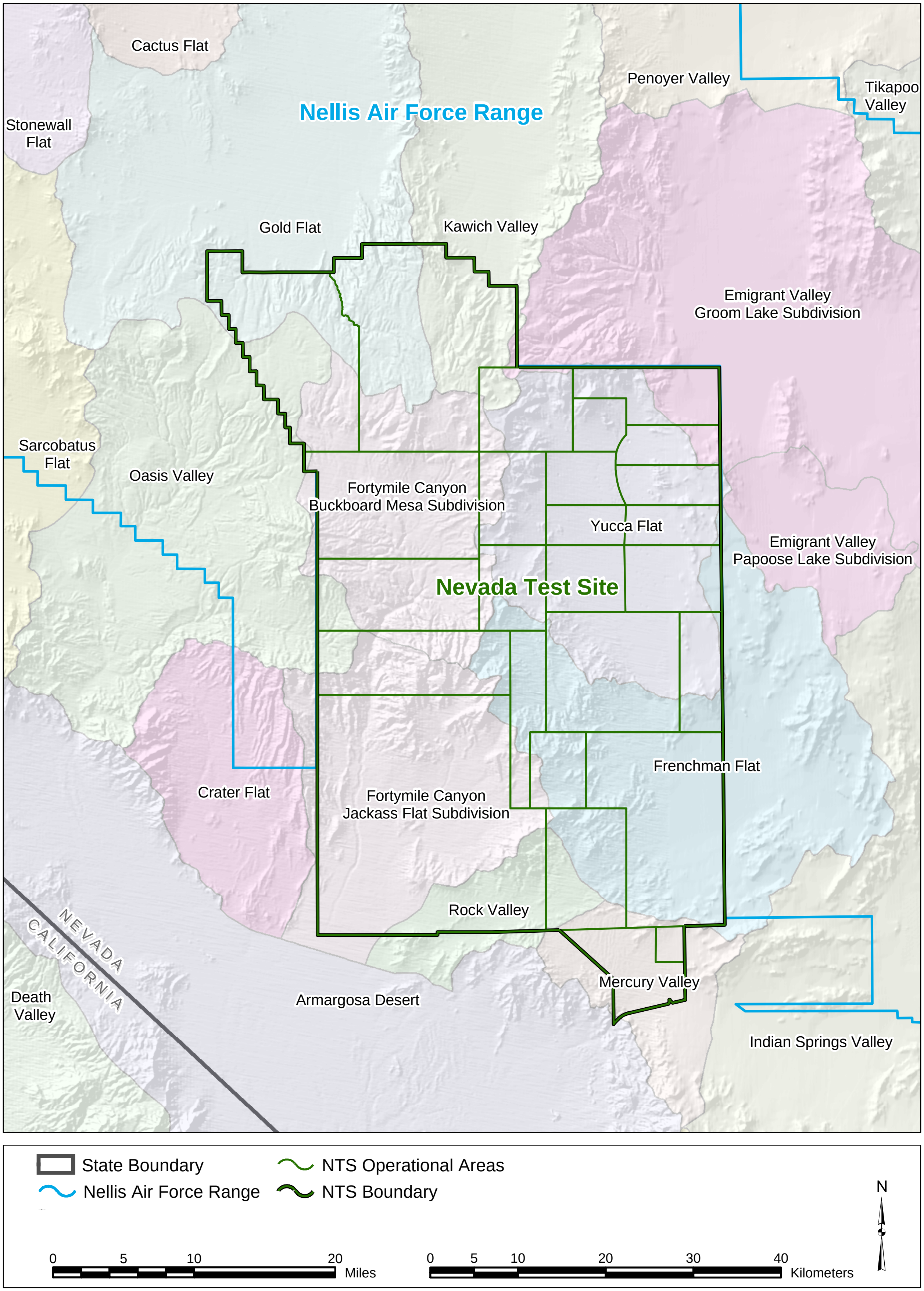

Figure 7.1 Hydrographic Subbasins on or near the Nevada Test Site

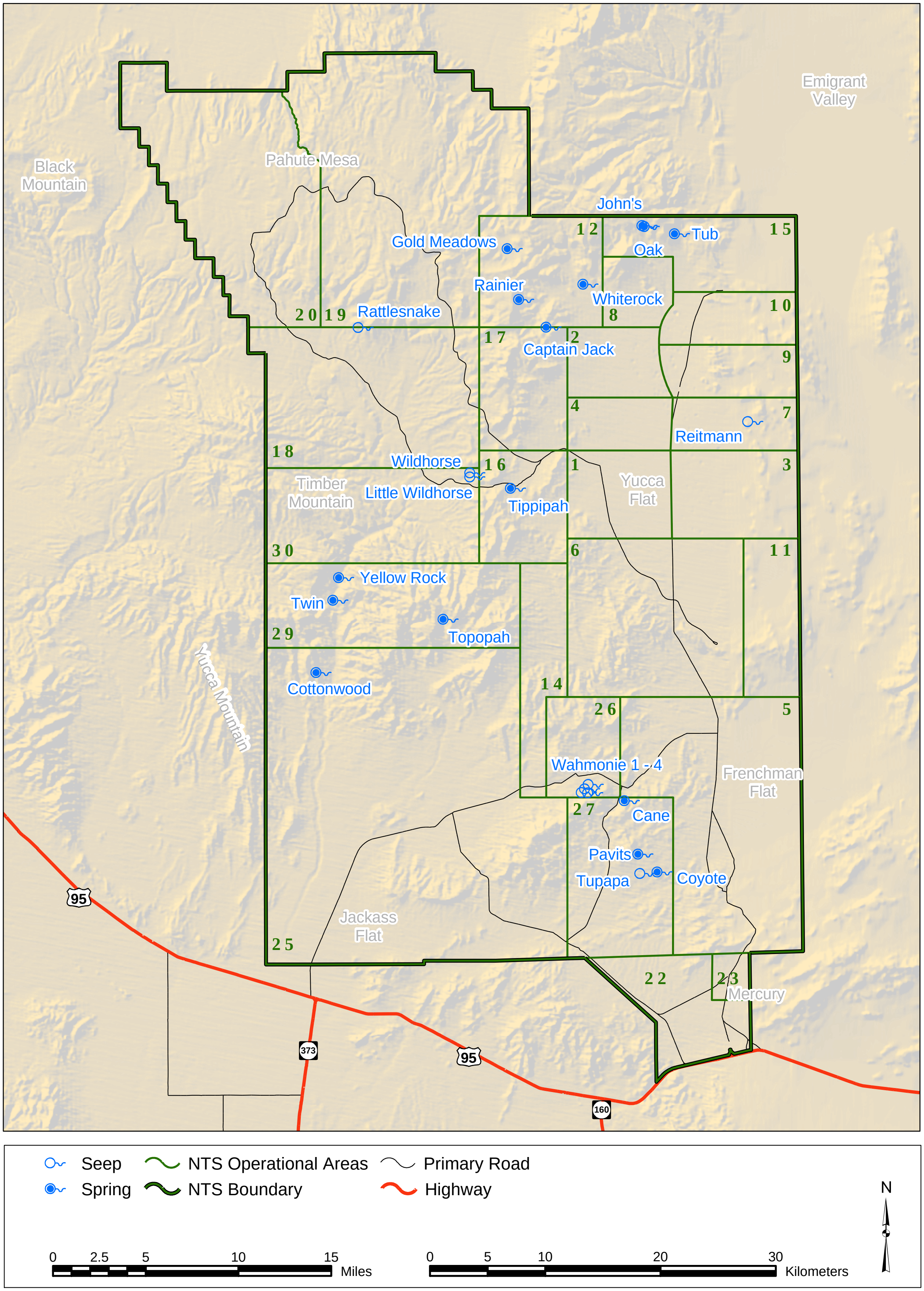

Figure 7.2 Natural Springs and Seeps on the Nevada Test Site

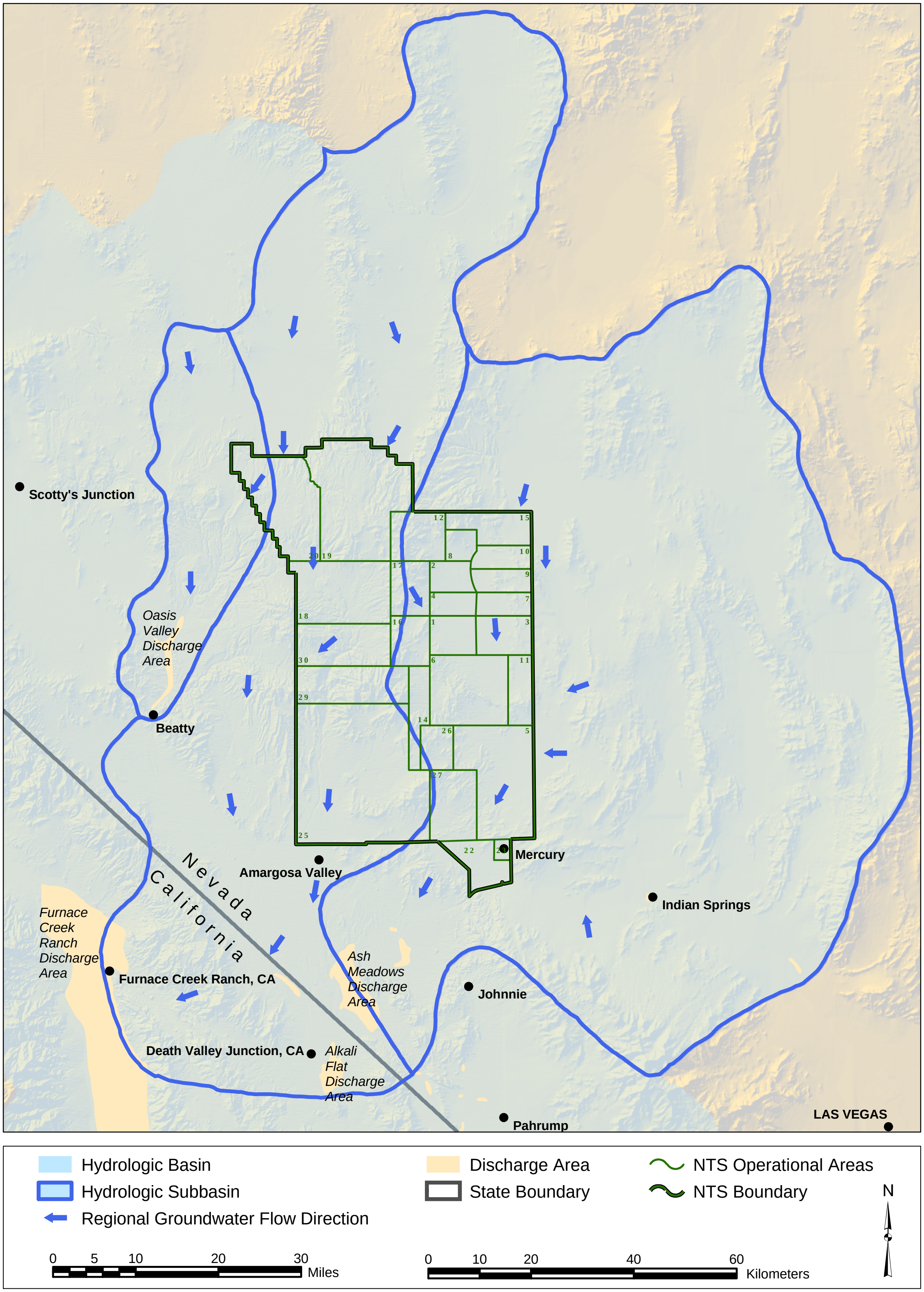

Figure 7.3 Groundwater Subbasins of the Nevada Test Site and Vicinity

The groundwater-bearing rocks at the NTS have been classified into several hydrogeologic units, of which the most important is the lower carbonate aquifer, a thick sequence of Paleozoic carbonate rock. This unit extends throughout the subsurface of central and southeastern Nevada, and is considered to be a regional aquifer (Winograd and Thordarson 1975; Laczniak, *et al*., 1996; IT 1996a). Various volcanic and alluvial aquifers are also locally important as water sources.

The depth to groundwater in wells at the NTS varies from about 210 m (690 ft) below the land surface under the Frenchman Flat playa in the southeastern NTS, to more than 610 m (2,000 ft) below the land surface in the northwestern NTS, beneath Pahute Mesa (IT 1996b; Reiner et al., 1995). Perched groundwater (isolated lenses of water lying above the regional groundwater level) occurs locally throughout the NTS, mainly within the volcanic rocks.

Recharge areas for the Death Valley groundwater system are the higher mountain ranges of central and southern Nevada, where there can be significant precipitation and snowmelt. Groundwater flow is generally from these upland areas to natural discharge areas in the south and southwest. Groundwater at the NTS is also derived from underflow from basins up-gradient of the area (Harrill *et al*., 1988). The direction of groundwater flow may locally be influenced by structure, rock type, or other geologic conditions. Based on existing water-level data (Reiner et al., 1995; IT 1996b; DOE 1998a) and flow models (IT 1996a; D'Agnese *et al*., 1997) the general groundwater flow direction within major water-bearing units beneath the NTS is to the south and southwest (Figure 7.3).

Most of the natural discharge from the Death Valley flow system is via transpiration by plants or evaporation from soil and playas in the Amargosa Desert and Death Valley. Groundwater discharge at the NTS is minor, consisting of small springs which drain perched water lenses and artificial discharge at a limited number of water supply wells.

Groundwater is the only local source of potable water on the NTS. The ten potable water wells that make up the NTS water system and supply wells for the various water systems in the area (town of Beatty, small mines, and local ranches) produce water for human and industrial use from the carbonate, volcanic, and alluvial aquifers. Water chemistry varies from a sodium-potassium-bicarbonate type to a calcium-magnesium-carbonate type, depending on the mineralogical composition of the aquifer source. Groundwater quality within aquifers of the NTS is generally acceptable for drinking water and industrial and agricultural uses (Chapman 1994), and meets the U.S. Environmental Protection Agency(EPA) drinking Water Standards (Chapman and Lyles 1993; Rose *et al*., 1997; BN 2000d).

7.3 HYDROLOGIC MODELING

The information in this section was compiled from various sources, as referenced throughout the discussion. However, the basic approach to these discussions is based on that taken to produce groundwater models for the various former test areas at the NTS for the Underground Test Area (UGTA) Program.

The Environmental Restoration Division of the National Nuclear Security Administration, Nevada Operation Office (NNSA/NV) initiated the UGTA project to study the effects of past underground nuclear testing in shafts and tunnels on groundwater at the NTS and surrounding areas. The multi-disciplinary UGTA investigation focuses on the geology and hydrology of the NTS to determine how contaminants are transported by groundwater flow. A regional three-dimensional computer groundwater model (IT 1996a; 1997) has already been developed to identify any immediate risk and to provide a basis for developing more detailed models of specific NTS test areas (designated as individual Corrective Action Units [CAUs]). The regional model constituted

Phase I of the UGTA project. The CAU-specific models, of which up to four are planned (geographically covering each of the six former NTS testing areas), comprise Phase II. To date one model has been built: Frenchman Flat (IT 1998). The Yucca Flat models are in progress. The results of the UGTA modeling project will be used to refine a monitoring network to ensure public health and safety.

Other hydrogeologic models for the area include those developed for the Yucca Mountain Program (YMP) (YMP 1998; Civilian Radioactive Waste Management System Management and Operating Contractor 1997) and the Death Valley regional groundwater flow system (D'Agnese *et al*., 1997). There are also site-specific models for the Radioactive Waste Management Sites (RWMSs) in Frenchman Flat, Area 5 (Shott *et al*., 1998) and Yucca Flat, Area 3 (BN 1997).

7.4 HYDROGEOLOGIC FRAMEWORK FOR THE NTS AND VICINITY

When the need for testing nuclear devices underground was recognized in the 1950s, among the first concerns was the effect testing would have on the groundwater of the area. One of the earliest nuclear tests conducted below the groundwater table (BILBY 1963) was designed in part to study explosion effects on groundwater and the movement in groundwater of radioactive byproducts from the explosion. Since that time, additional studies at various scales have been conducted to aid in the understanding of groundwater flow at the NTS. The current understanding of the regional groundwater flow at the NTS in derived from work by Winograd and Thordarson (1975), which was summarized and updated by Laczniak *et al*. (1996), and has further been developed by the UGTA hydrogeologic modeling team (IT 1996c, 1998b; Drellack and Prothro 1997; BN 2001a).

Winograd and Thordarson (1975) established a hydrogeologic framework, incorporating the work of Blankennagel and Weir (1973) who defined the first hydrogeologic units to address the complex hydraulic properties of volcanic rocks. Hydrogeologic units (HGUs) are used to categorize lithologic units according to their ability to transmit groundwater, which is mainly a function of their primary lithologic properties, degree of fracturing, and secondary mineral alteration. Hydrostratigraphic units (HSUs) for the NTS volcanic rocks were first defined during the UGTA modeling initiative (IT 1996a). HSUs are groupings of contiguous stratigraphic units that have a particular hydrogeologic character, such as aquifer (unit through which water moves readily) or confining unit (unit that generally is impermeable to water movement) (see Seaber [1988] for a discussion of hydrostratigraphy). The concept of HSUs is very useful in volcanic terrains where stratigraphic units can vary greatly in hydrologic character both laterally and vertically.

The rocks of the NTS have been classified for hydrologic modeling using this two-level classification scheme, in which HGUs are grouped to form HSUs (IT 1996a). An HSU may consist of several HGUs but is defined so that a single general type of HGU dominates (for example, mostly welded-tuff and vitric-tuff aquifers or mostly tuff confining units).

The hydrogeologic framework used for most groundwater flow and contaminant transport models for UGTA and other NTS programs are built on the work of Blankennagle and Weir (1973), Winograd and Thordarson (1975), and Laczniak *et al*., (1996). New units and additional detail have been added to the basic framework definition, but the systems developed by these early workers remain the best way to understand the groundwater of the NTS region. The following paragraphs describe the current understanding of the hydrogeologic framework of the NTS, first addressing HGUs, then describing the main HSUs.

HYDROGEOLOGIC UNITS OF THE NTS AREA

All the rocks of the NTS and vicinity can be classified as one of nine hydrogeologic units, which include the alluvial aquifer, four volcanic hydrogeologic units, two intrusive units, and two hydrogeologic units that represent the pre-Tertiary rocks (Table 7.1).

The deposits of alluvium (alluvial aquifer) fill the main basins of the NTS, and generally consist of a loosely consolidated mixture of boulders, gravel, and sand derived from volcanic and Paleozoic sedimentary rocks (Slate *et al*., 1999). The volcanic rocks of the NTS and vicinity can be categorized into four hydrogeologic units based on primary lithologic properties, degree of fracturing, and secondary mineral alteration. In general, the altered (typically zeolitized, or, hydrothermally altered near caldera margins) volcanic rocks act as confining units (tuff confining unit), and the unaltered rocks form aquifers. The volcanic aquifer units can be further divided into welded-tuff aquifers or vitric-tuff aquifers (depending upon the degree of welding) and lava-flow aquifers. The denser rocks (welded ash-flow tuffs and lava flows) tend to fracture more readily, and therefore have relatively high permeability (Blankennagel and Weir, 1973; Winograd and Thordarson 1975; Laczniak *et al*., 1996; IT 1997,1996c; Prothro and Drellack 1997).

An additional igneous HGU, the intercaldera intrusive confining unit (IICU), was defined for the Pahute Mesa hydrogeologic model (BN 2001a). Conceptually, an IICU underlies each of the calderas of the southwest Nevada volcanic field (SWNVF), and though no drill holes penetrate theses rocks, it is presume these bodies range from highly altered, highly injected/intruded country rock to granite. The IICU is considered to behave as a confining unit due to low primary porosity and low permeability, and because most fractures are probably filled with secondary minerals.

The pre-Tertiary sedimentary rocks at the NTS and vicinity are also categorized as aquifer or confining unit HGUs based on lithology. The silicic clastic rocks (quartzites, siltstones, shales) tend to be aquitards or confining units, while the carbonates (limestone and dolomite) tend to be aquifers (Winograd and Thordarson 1975; Laczniak *et al*., 1996). The granite confining unit (GCU) is considered to behave as a confining unit due to low primary porosity, low permeability, and because most fractures are probably filled with secondary minerals.

HYDROSTRATIGRAPHIC UNITS OF THE NTS AREA

The rocks at the NTS and vicinity are grouped into roughly sixty HSUs. The more important and widespread HSUs in the area are discussed separately in this section. Additional information regarding more restricted HSUs is presented in Section 7.5.

Lower Clastic Confining Unit (LCCU)

The Proterozoic to Middle-Cambrian rocks are largely quartzite and silica-cemented siltstone. Although these rocks are brittle and commonly fractured, secondary mineralization seems to have greatly reduced formation permeability (Winograd and Thordarson 1975). These units make up the LCCU, which is considered to be the regional hydrologic basement (IT, 1996a). The LCCU is interpreted to underlie the entire region except at the calderas. Where it is in a structurally high position, the LCCU may act as a barrier to deep regional groundwater flow.

Lower Carbonate Aquifer (LCA)

The LCA consists of thick sequences of Middle Cambrian through Upper Devonian carbonate rocks. This HSU serves as the regional aquifer for most of southern Nevada, and locally may be as thick as 5,000 m (16,400 ft) (Cole 1997; Cole and Cashman 1999). The LCA is present under most of the area except where the LCCU is structurally high and at the calderas.

Transmissivities of these rocks differ from place to place, apparently reflecting the observed differences in fracture and fault densities and characteristics (Winograd and Thordarson, 1975).

Upper Clastic Confining Unit (UCCU)

Upper Devonian and Mississippian silicic clastic rocks in the NTS vicinity are assigned to the Eleana Formation and the Chainman Shale (Cashman and Trexler 1991; Trexler et al., 1996). Both formations are grouped into the UCCU. At the NTS this HSU is found mainly within a north-south band along the western portion of Yucca Flat. It is a significant confining unit, and in many places forms the footwall of the Belted Range and Control Point (CP) thrust faults.

Lower Carbonate Aquifer, Upper Thrust Plate (LCA3)

Cambrian through Devonian, mostly carbonate, rocks that occur in the hanging wall of the Belted Range and CP thrust faults are designated as LCA3. These rocks are equivalent stratigraphically to the LCA, but are structurally separated from the LCA by the Belted Range thrust fault. The LCA3 is patchily distributed as remnant thrust blocks, particularly along the western and southern sides of Yucca Flat (at Mine Mountain and the CP Hills), at Calico Hills, and at Bare Mountain.

Mesozoic Granite Confining Unit (MGCU)

The Mesozoic era is represented at the NTS only by intrusive igneous rocks. Cretaceous-age granitic rocks are exposed at two locations: in northern Yucca Flat area, at the Climax stock; and the Gold Meadows stock, which lies 12.9 km (8 mi) west of the Climax stock, just north of Rainier Mesa (Snyder 1977; Bath *et al.*, 1983) (Figure 7.4). The two are probably related in both source and time and, may be connected at depth (Jachens 1999). Because of its low intergranular porosity and permeability, plus the lack of inter-connecting fractures (Walker 1962) the MGCU is considered a confining unit. The Climax and Gold Meadows intrusives are grouped into the MGCU HSU.

Tertiary and Quaternary Hydrostratigraphic Units

Tertiary- and Quaternary-age strata at the NTS are organized into dozens of HSUs. Nearly all are of volcanic origin, except the alluvial aquifer, which is the uppermost HSU. These rocks are important because (1) most of the underground nuclear tests at the NTS were conducted in these units, (2) they constitute a large percentage of the rocks in the area, and (3) they are inherently complex and heterogeneous. As pointed out in Section 7.4, the volcanic rocks are divided into aquifer or confining unit according to lithology and secondary alteration.

More discussion of these HSUs is provided in Section 7.5 where the hydrogeology of each underground test area at the NTS is addressed. Detailed information can be found in the documentation packages for the UGTA CAU-scale hydrogeologic models (IT 1996a, 1998; Gonzales and Drellack 1999; BN 2001a).

Alluvial Aquifer (AA)

The alluvium throughout most of the NTS is a loosely consolidated mixture of detritus derived from silicic volcanic and Paleozoic sedimentary rocks, ranging in particle size from clay to boulders. Sediment deposition is largely in the form of alluvial fans (debris flows, sheet wash, and braided streams) which coalesce to form discontinuous, gradational, and poorly sorted deposits. Eolian sand, playa deposits and rare basalt flows are also present within the alluvium section of some valleys. The alluvium thickness in major valleys (e.g. Frenchman Flat and Yucca Flat) generally ranges from about 30 m (100 ft) to over 1,138 m (3,732 ft) at Well ER-5-4.

The alluvial aquifer HSU is confined primarily to the basins of the NTS (Figure 7.4). However, because the water table in the vicinity is moderately deep, the alluvium is generally unsaturated, except in the deep sub-basins of some valleys. These sediments are porous, and thus, have high storage coefficients. Transmissivities may also be high, particularly in the coarser, gravelly beds.

STRUCTURAL CONTROLS

Geologic structures are an important component of the hydrogeology of the area. Structures define the geometric configuration of the area, including the distribution, thickness, and orientation of units. Synvolcanic structures, including caldera faults and some normal faults had strong influence on depositional patterns of many of the units. Juxtapositioning of units with different hydrologic properties across faults may have significant hydrogeologic consequences. Also, faults may act as either conduits of groundwater flow, depending on the difference in permeability between a fault zone and the surrounding rocks. This is partially determined by whether the fault zone is characterized by open fractures, or if it is associated with fine-grained gouge or increased alteration.

Five main types of structural features exist in the area:

- Thrust faults (e.g. Belted Range and CP thrusts).
- Normal faults (e.g. Yucca and West Greeley faults).
- Transverse faults and structural zones (e.g. Rock Valley and Cane Spring faults).
- Calderas (e.g. Timber Mountain and Silent Canyon caldera complexes).
- Detachment faults (e.g. Fluorspar Canyon - Bullfrog Hills detachment fault).

The Belted Range thrust fault is the principle pre-Tertiary structure in the NTS region, and thus controls the distribution of pre-Tertiary rocks in the area. The fault can be traced or inferred from Bare Mountain just south of the southwest corner of the NTS area to the northern Belted Range, just north of the NTS, a distance of more than 130 km. It is an east-vergent thrust fault that generally places late Proterozoic to early Cambrian rocks over rocks as young as Mississippian. Several imbricate thrust faults occur east of the main thrust fault. Deformation related to the Belted Range thrust fault occurred sometime between 100 to 250 Ma. Lesser thrusts of similar age are mapped in the area (e.g. the CP and Spotted Range thrusts).

Normal faults in the area are related mainly to basin-and-range extension (e.g. Yucca fault in Yucca Flat and West Greeley fault on Pahute Mesa). Most of them likely developed during and after the main phase of volcanic activity of the SWNVF (Sawyer *et al.*, 1994). The majority of these faults are northwest- to northeast-striking, high angle faults. However, the exact locations, amount of offset along the faults, and character of the faults become increasingly uncertain with depth.

Calderas are probably the most hydrogeologically important features in the NTS area. Volcano-tectonic and geomorphic processes related to caldera development result in abrupt and dramatic lithologic and thickness changes across caldera margins. Consequently, caldera margins (i.e. faults) separate regions with considerably different hydrogeologic character. At least six major calderas have been identified in the SWNVF, a multi-caldera silicic volcanic field that formed by the voluminous eruption of zoned ignimbrites between 16 and 7.5 million years ago (Sawyer et al., 1994). From oldest to youngest the calderas are: Grouse Canyon, Area 20, Claim Canyon, Rainier Mesa, Ammonia Tanks, and Black Mountain calderas. A comprehensive review of past studies and the evolution of concepts on calderas of the SWNVF during the period from 1960 to 1988 is presented in Byers *et al.*, 1989.

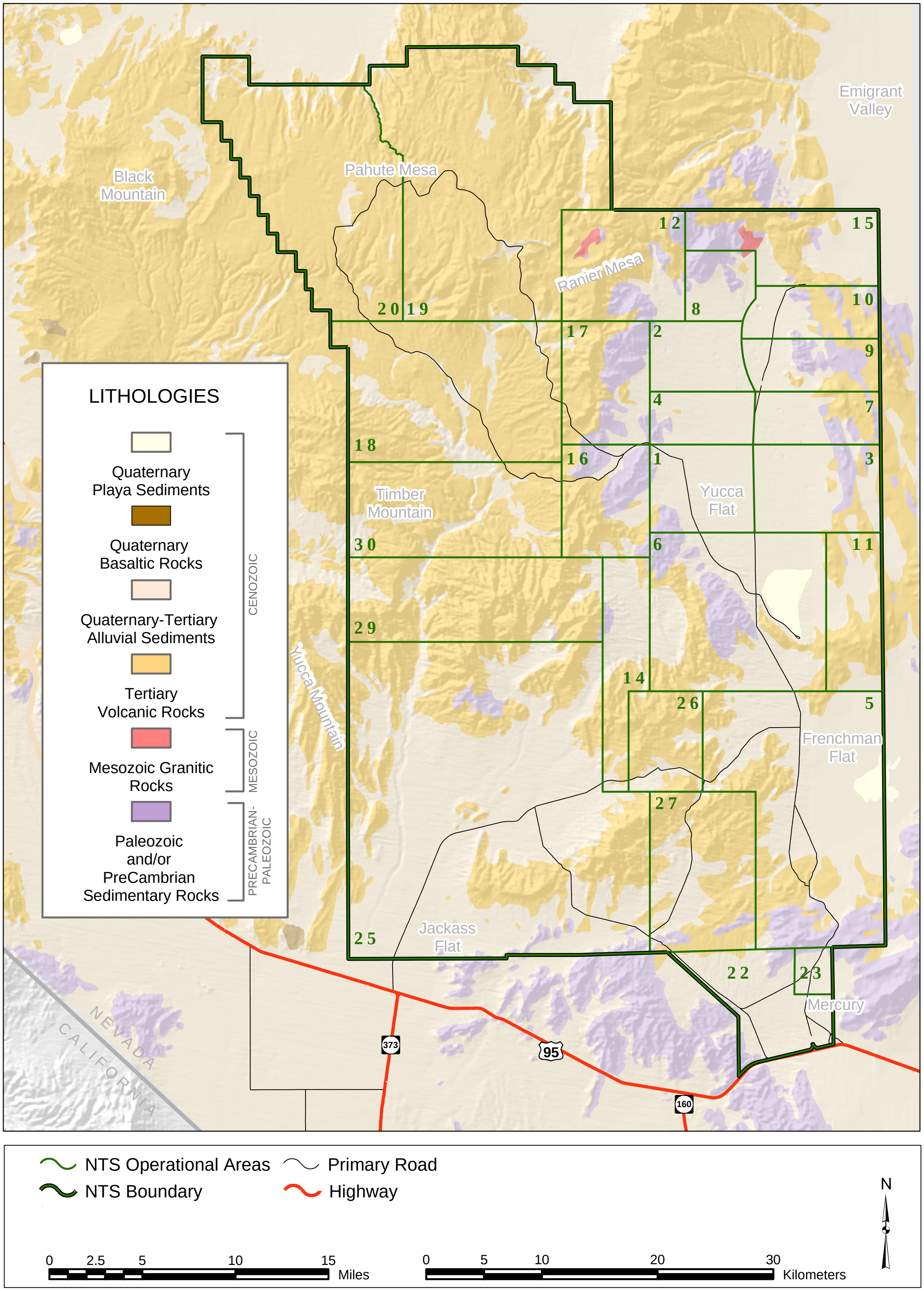

Figure 7.4 Generalized Geologic Map of the Nevada Test Site and Vicinity

HYDRAULIC PROPERTIES

It is difficult to give precise hydraulic conductivity values for NTS HSUs because of their spacial variability (aquifer heterogeneity). Volcanic rocks typically are extremely variable in lithologic character both laterally and vertically, which accounts for some of the observed heterogeneity. In some areas, units of different character are so finely interbedded that they are assigned to a composite unit (e.g. lava flows embedded within zeolitized bedded tuffs) whose overall hydrologic properties are variable. Another cause of heterogeneity is the irregular distribution of the effects of hydrothermal alteration. Hydraulic properties have rarely been measured for specific HSUs, as borehole hydraulic test intervals tended to span HSU contacts. However, laboratory and field measurements of hydraulic conductivity, flow rates, and temperature profiles indicate that almost all of the groundwater at the NTS is moving through fractures (GeoTrans 1995).

General Hydraulic Characteristics of NTS Rocks

The characteristics of rocks that control the density and character of fractures are the primary determinants of their hydraulic properties, and most hydraulic heterogeneity ultimately is related to fracture characteristics such as fracture density, openness, orientation, and other properties. Secondary fracture-filling minerals can drastically obstruct the flow through or effectively seal an otherwise transmissive formation (Drellack *et al.*, 1997; IT 1996c). Fracture density typically increases with proximity to faults, potentially increasing the hydraulic conductivity of the formation; however, the hydrologic properties of faults are not well known. Limited data suggest that the full spectrum of hydraulic properties, from barrier to conduit, may be possible (Blankennagel and Weir 1973; Faunt 1998). Prediction of the influence of any fault on the hydrologic system thus is made very difficult by the uncertainties associated with estimating the hydraulic properties of that fault, complicated by the potential for the fault to juxtapose permeable and less permeable water-bearing units.

Table 7.2 presents a summary of the hydrologic properties of NTS HGUs. The lowest transmissivity values in volcanic rocks at the NTS are typically associated with non-welded ash-flow tuff and bedded tuff (air-fall and reworked tuffs). Although interstitial porosity may be high, the interconnectivity of the pore space is poor, and these relatively incompetent rocks tend not to support open fractures. Secondary alteration of these tuffs (most commonly, zeolitization) ultimately yields a very impermeable unit. As described in Section 7.4, these zeolitized tuffs are considered to be confining units. The equivalent unaltered bedded and non-welded tuffs are considered to be vitric-tuff aquifers, and have intermediate transmissivities.

In general, the most transmissive rocks tend to be moderately to densely welded ash-flow tuffs (welded-tuff aquifer), rhyolite lava flows (lava-flow aquifer), and carbonate rocks (limestone and dolomite). Although their interstitial porosity is low, these competent lithologies tend to be highly fractured, and groundwater flow through these rocks is largely through an interconnected network of fractures (Blankennagel and Weir 1973; GeoTrans 1995).

Effect of Underground Nuclear Explosions on Hydraulic Characteristics

Underground nuclear explosions may affect hydraulic properties of the geologic medium (both long-term and short-term effects). Effects include enhanced permeability from shock-induced fractures, the formation of vertical conduits (e.g., collapse chimneys), and elevated water levels (mounding and over-pressurization of saturated low-permeability units). However, these effects tend to be localized (Borg *et al.*, 1976; Brikowski 1991; Allen *et al.*, 1997), and usually are addressed in the UGTA program on a case-by-case basis or in sub-CAU-scale models, rather than in regional or CAU-level models.

7.5 HYDROGEOLOGY OF THE NTS FORMER TEST AREAS

Most NTS underground nuclear detonations were conducted in three main test areas: (1) Yucca Flat, (2) Pahute Mesa, and (3) Rainier Mesa (including Aqueduct Mesa). Underground tests in Yucca Flat and Pahute Mesa typically were conducted in vertical drill holes, whereas almost all tests conducted in Rainier Mesa were tunnel emplacements. A total of 85 underground tests (85 detonations) were conducted on Pahute Mesa, including about 19 high-yield detonations (200 kilotons [kt] or more). Rainier Mesa hosted 61 underground tests (62 detonations), almost all of which were relatively low-yield (generally less than 20 kt) tunnel-based weapons-effects tests. Yucca Flat was the most extensively utilized test area, hosting 659 underground tests (747 detonations), four of which were high-yield detonations (Allen *et al*., 1997).

In addition to the three main test areas, underground nuclear tests were conducted in Frenchman Flat (ten tests), Shoshone Mountain (six tests), the Oak Spring Butte/Climax Mine area (three tests), the Buckboard Mesa area (three tests), and Dome Mountain (one test with five detonations) (Allen *et al*., 1997). It should be noted that these totals include nine cratering tests (13 total detonations) conducted in various areas of the NTS. Table 7.3 is a synopsis of information about each underground test area at the NTS, and Figure 7.5 is a map showing the areal distribution of underground nuclear tests conducted at the NTS.

The location of each underground nuclear tests is classified as a Corrective Action Site (CAS). These in turn have been grouped into six CAUs, according to the Federal Facilities Agreement and Consent Order (FFACO 1996) between the DOE and the state of Nevada. In general, the CAUs relate to geographical testing areas on the NTS (Figure 7.5). The hydrogeology of the NTS former test areas is summarized in the following sections.

FRENCHMAN FLAT

The Frenchman Flat CAU consists of ten CASs located in the northern part of NTS Area 5 and southern part of Area 11 (Figure 7.5). The detonations were conducted in vertical emplacement holes and two mined shafts. Nearly all the tests were conducted in alluvium above the water table.

Geologic Overview of Frenchman Flat

The stratigraphic section for the Frenchman Flat area consists of (from oldest to youngest) Proterozoic and Paleozoic clastic and carbonate rocks, Tertiary sedimentary and tuffaceous sedimentary rocks, Tertiary volcanic rocks, and Quaternary and Tertiary alluvium (Slate *et al*., 1999). In the northernmost portion of Frenchman Flat, middle to upper Miocene volcanic rocks that erupted from calderas located to the northwest of Frenchman Flat unconformably overlie Ordovician carbonate and clastic rocks. To the south, these volcanic units, including the Ammonia Tanks Tuff, Rainier Mesa Tuff, Topopah Spring Formation, and Crater Flat Group, either thin considerably, interfinger with coeval sedimentary rocks, or pinch out altogether (IT 1998b). Upper-middle Miocene tuffs, lavas, and debris flows from the Wahmonie volcanic center located just west of Frenchman Flat dominate the volcanic section beneath the western portion of the valley. To the south and southeast, most of the volcanic units are absent and Oligocene to middle Miocene sedimentary and tuffaceous sedimentary rocks, which unconformably overlie the Paleozoic rocks in the southern portion of Frenchman Flat, dominate the Tertiary section (Prothro and Drellack 1997). In most of the Frenchman Flat area, upper Miocene to Holocene alluvium covers the older sedimentary and volcanic rocks (Slate *et al*., 1999). Alluvium thicknesses range from a thin veneer along the valley edges to perhaps as much as 1,158 m (3,800 ft) in north central Frenchman Flat.

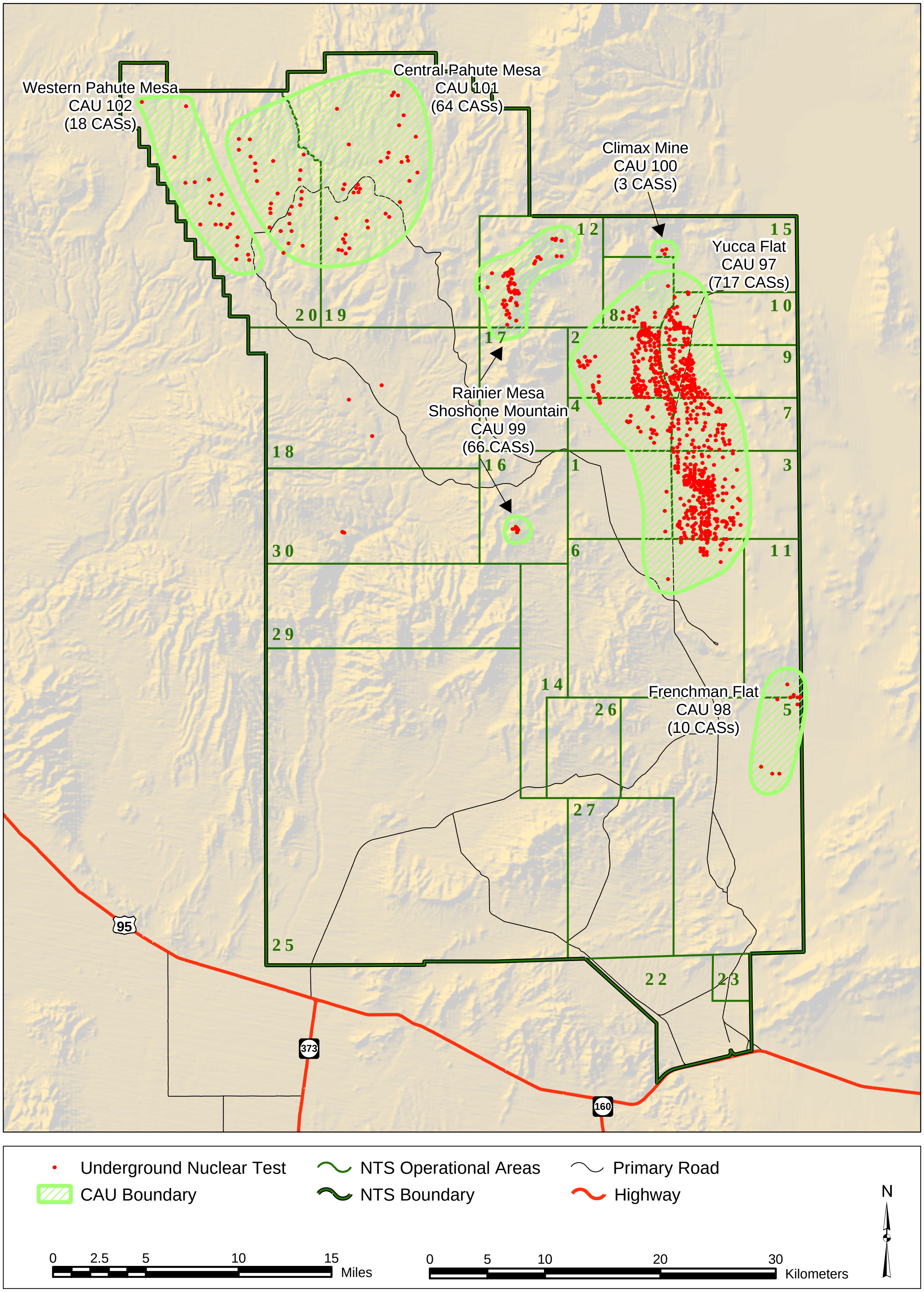

Figure 7.5 Corrective Action Units and Corrective Action Sites on the Nevada Test Site

The structural geology of the Frenchman Flat area is complex. During the late Mesozoic, the region was subjected to compressional deformation which resulted in folding, thrusting, uplift, and erosion of the pre-Tertiary rocks (Barnes et al., 1982). Beginning approximately 16 million years ago, the region has undergone extensional deformation, during which the present basin-and-range topography was developed and the Frenchman Flat basin was formed (Ekren et al., 1968). In the immediate vicinity of Frenchman Flat, extensional deformation has produced east-northeast-trending, left-lateral strike-slip faults and generally north-trending normal faults that displace the Tertiary and pre-Tertiary rocks. Beneath Frenchman Flat, major west-dipping normal faults merge and are probably contemporaneous with strike-slip faults beneath the southern portion of the basin (Grauch and Hudson 1995). Movement along the faults has created a series of relatively narrow, east-dipping, half-graben sub-basins elongated in a northern direction (Figure 7.6).

Hydrogeology Overview of Frenchman Flat

The hydrogeology of Frenchman Flat is fairly complex, but is typical of the NTS area. Although many of the HGU- and HSU-building blocks developed for the NTS vicinity are applicable to the Frenchman Flat basin, several features make Frenchman Flat unique.

- Significant thickness of older (Oligocene to Miocene) Tertiary sediments.
- Proximity to the Wahmonie volcanic center.
- Distribution of the younger volcanic aquifers.
- Presence of northeast-striking strike-slip faults.

The strata in the Frenchman Flat area have been subdivided into five Tertiary-age HSUs (including the Quaternary/Tertiary alluvium) and three pre-Tertiary HSUs to serve as layers for the UGTA Frenchman Flat CAU groundwater model (IT 1998b). In descending order these units are: the AA, the Timber Mountain aquifer (TMA), the Wahmonie volcanic confining unit (WVCU), the tuff confining unit (TCU), the volcaniclastic confining unit (VCU), the LCA, and the LCCU (Table 7.4).

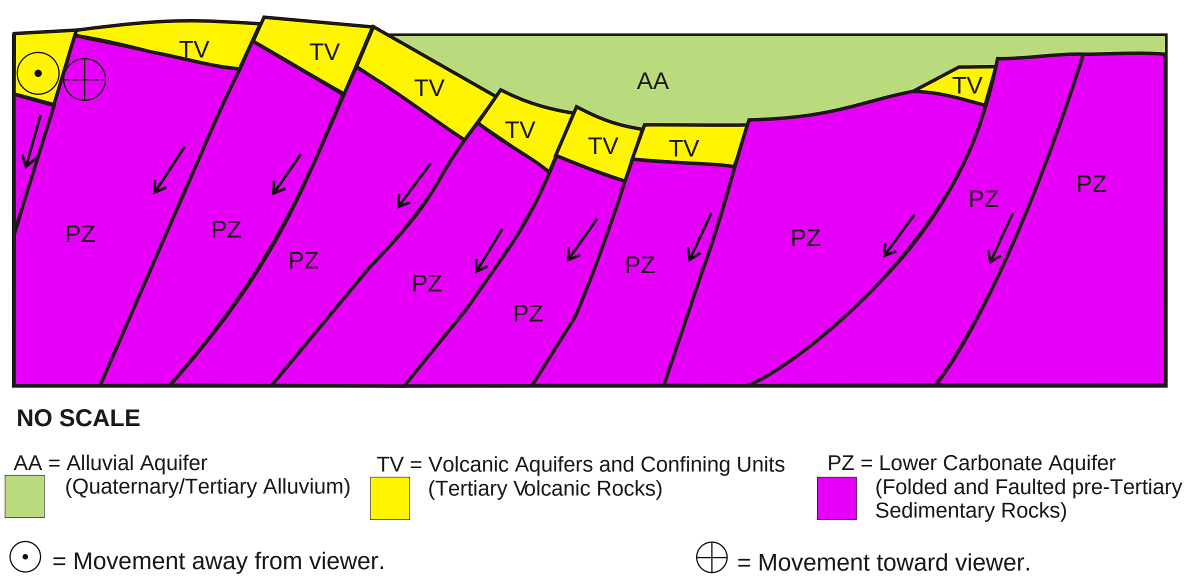

Figure 7.6 Conceptual East-West Cross Section Through Frenchman Flat Showing Sub-Basins Formed by Fault Blocks

Water-level Elevation and Groundwater Flow Direction

The depth to the static water level (SWL) in Frenchman Flat ranges from 210 m (690 ft) near the central playa to more the 350 m (1,150 ft) at the northern end of the valley. The SWL is generally located within the AA, TMA, WVCU or TCU. In the deeper, central portions of the basin, more than half of the alluvium section is saturated. Water-level elevation data in the AA indicate a very flat water table (Blout et al., 1994; IT 1998b). Unfortunately, the poor areal distribution of wells precludes high confidence in any inferred groundwater flow direction for the shallow (alluvial) aquifer.

Water-level data for the LCA in the southern part of the NTS are limited, but indicate a fairly low gradient in the Yucca Flat, Frenchman Flat, and Jackass Flats area. This gentle gradient implies a high degree of hydraulic continuity within the aquifer, presumably due to high fracture permeability (Laczniak et al., 1996). Furthermore, the similarity of the water levels measured in Paleozoic rocks (LCA) in Yucca Flat and Frenchman Flat implies that, at least for deep interbasin flow, there is no groundwater barrier between the two basins. Inferred regional groundwater flow through Frenchman Flat is to the south-southwest toward discharge areas in Ash Meadows (Figure 7.3). An increasing westward flow vector in southern NTS may be due to preferential flow paths subparallel to the east-northeast-trending Rock Valley fault (Grauch and Hudson 1995) and/or a northward gradient from the Spring Mountain recharge area (IT 1996a; b).

Groundwater elevation measurements for wells completed in the AA and TMA are higher than those in the underlying LCA (IT 1996b; 1998b). This implies a downward gradient. This apparent semi-perched condition is believed to be due to the presence of intervening TCU and VCU units.

In the effort to predict and model potential pathways for radiological contaminants from nuclear tests conducted in the AA to reach the regional groundwater system, the possibility of communication between the local aquifers, AA or TMA, and the regional LCA must be addressed. Such pathways could be possible, as explored in the following scenarios:

- Communication via a fault (enhanced permeability due to fracturing near the fault).
- Juxtaposition of the AA or TMA against the LCA due to displacement along a fault.
- Direct communication from the AA and the TMA to the LCA where the TCU, WVCU, or VCU are absent and the AA is in direct contact with the LCA.

YUCCA FLAT

The Yucca Flat/Climax Mine CAU consists of 717 CASs located in NTS Areas 1, 2, 3, 4, 6, 7, 8, 9, 10, and three CASs located in Area 15 (Figure 7.5). These tests were typically conducted in vertical emplacement holes and a few related tunnels (Table 7.3).

The Yucca Flat and Climax Mine testing area were originally defined as two separate CAUs (CAU 97 and CAU 100) in the FFACO (1996) because the geologic frameworks of the two areas are distinctly different. The Yucca Flat underground nuclear tests were conducted in alluvial, volcanic, and carbonate rocks, whereas the Climax Mine tests were conducted in an igneous intrusion in northern Yucca Flat. However, particle-tracking simulations performed during the regional evaluation (IT 1997) indicated that the local Climax Mine groundwater flow system merges into the much larger Yucca Flat groundwater flow system during the 1,000-year time period of interest, so the two areas were combined into the single CAU 97.

Yucca Flat was the most heavily used testing area on the NTS (Figure 7.5). The alluvium and tuff formations provide many characteristics advantageous to the containment of nuclear explosions. They are easily mined or drilled. The high-porosity overburden (alluvium and vitric tuffs) will accept and depressurize any gas which might escape the blast cavity. The deeper tuffs are zeolitized, which creates a nearly impermeable confining unit. The zeolites also have absorptive and “molecular sieve” attributes which severely restrict or prevent the migration of radionuclides. The deep water table (503 m [1,650 ft]) provides additional operational and environmental benefits.

This section provides descriptions of the geologic and hydrogeologic setting of the Yucca Flat area, as well as a discussion of the hydrostratigraphic framework. This summary was compiled from various sources, including Gonzales and Drellack (1999), Winograd and Thordarson (1975), Laczniak *et al*., (1996), Byers *et al*., (1989), and Cole (1997) where additional information can be found.

Geology Overview of Yucca Flat

Yucca Flat is a topographically closed basin with a playa at its southern end (Figure 7.4). The geomorphology of Yucca Flat is typical of the arid, inter-mountain basins found throughout the Basin and Range province of Nevada and adjoining states. Faulted and tilted blocks of Tertiary-age volcanic rocks and underlying Precambrian and Paleozoic sedimentary rocks form low ranges around the basin (Figure 7.4). These rocks also compose the “basement” of the basin, which is now covered by alluvium.

The Precambrian and Paleozoic rocks of the NTS area consist of approximately 11,300 m (37,000 ft) of carbonate and silicic clastic rocks (Cole 1997). These rocks were severely deformed by compressional movements during Mesozoic time, which resulted in the formation of folds and thrust faults (e.g. Belted Range and CP thrust faults). During the middle Late Cretaceous granitic bodies (such as the Climax stock in northern Yucca Flat) intruded these deformed rocks (Maldonado 1977; Houser and Poole 1960). During Cenozoic time, the sedimentary and intrusive rocks were buried by thick sections of volcanic material deposited in several eruptive cycles from source areas in the SWNVF. The volcanic rocks include primarily ash-flow tuffs, ash-fall tuffs, and reworked tuffs, whose thicknesses and extents vary partly due to the irregularity of the underlying depositional surface, and partly due to the presence of topographic barriers and windows between Yucca Flat and the source areas to the north and west.

Large-scale normal faulting began in the Yucca Flat area in response to regional extensional movements near the end of this period of volcanism. This faulting formed the Yucca Flat basin, and as fault movement continued, blocks between faults were down-dropped and tilted, creating subbasins within the Yucca Flat basin. Over the last several million years, gradual erosion of the highlands that surround Yucca Flat has deposited a thick blanket of alluvium on the tuff section. The thickness of the alluvium in the Yucca Flat basin varies as a function of the topography of the underlying deposits and due to continuing movements along faults during alluvium deposition.

The structure of the pre-Tertiary rocks is complex and poorly known, but it is important because the pre-Tertiary section is very thick and extensive and includes units which form regional aquifers. The main pre-Tertiary structures in the Yucca Flat area are related to the east-vergent Belted Range thrust fault which has placed Late Proterozoic to Cambrian-age rocks (LCA3) over rocks as young as Late Mississippian (UCCU) (Cole 1997; Cole and Cashman 1999). In several places along the western and southern portions of Yucca Flat, east-vergent structures related to the Belted Range thrust were deformed by younger west-vergent structural activity (Cole and Cashman 1999). This west-vergent deformation is related to the CP thrust fault which also placed LCA3 over UCCU (Caskey and Schweickert 1992).

The more recent large-scale extensional faulting in the Yucca Flat area is significant because the faults have profoundly affected the hydrogeology of the Tertiary volcanic units by controlling to a large extent their alteration potential and final geometry. In addition, the faults themselves may facilitate flow of potentially contaminated groundwater from sources in the younger rocks into the underlying regional aquifers. The major basin-forming faults generally strike in a northerly direction, and relative offset is typically down to the east (e.g. Yucca, Topgallant, and Carpetbag faults). Movement along the Yucca fault in central Yucca Flat indicates deformation in the area has continued into the Holocene (Hudson 1992).

The configuration of the Yucca Flat basin is illustrated on the generalized west-east cross section shown in Figure 7.7. The cross section is simplified to show the positions of only the primary hydrostratigraphic units in the region. This cross section provides a conceptual illustration of the irregular Precambrian and Paleozoic rocks overlain by the Tertiary volcanic units, and the basin-filling alluvium at the surface. The main Tertiary-age, basin-forming large-scale normal faults are also shown.

Hydrogeology Overview of Yucca Flat

All the rocks of the Yucca Flat study area can be classified as one of eight hydrogeologic units, which include the alluvial aquifer, four volcanic hydrogeologic units, an intrusive unit, and two hydrogeologic units that represent the pre-Tertiary rocks (Table 7.1).

The strata in the Yucca Flat area have been subdivided into eleven Tertiary-age HSUs (including the Tertiary/Quaternary alluvium), one Mesozoic intrusive HSU, and six Paleozoic HSUs (Gonzales and Drellack 1999). These units are listed in Table 7.5, and several of the more important HSUs are discussed in the following paragraphs. The pre-Tertiary HSUs in Yucca Flat are as defined in Section 7.4.

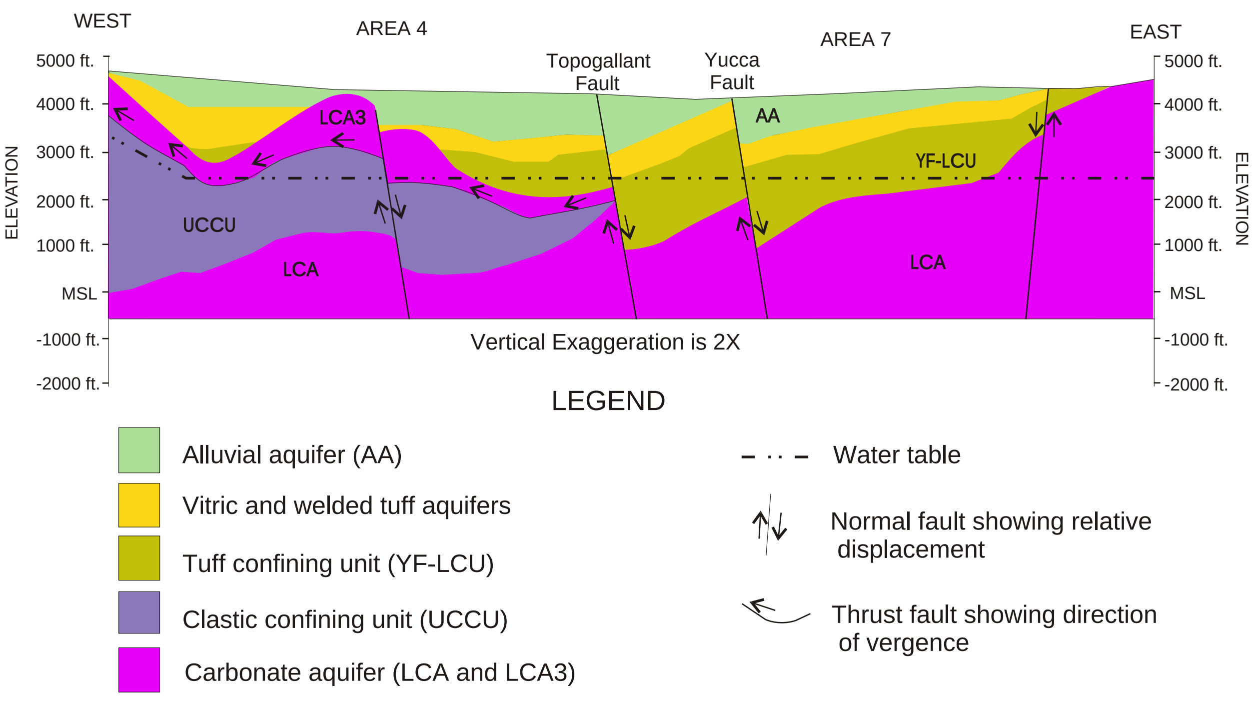

Figure 7.7 Generalized West-East Hydrogeologic Cross Section Through Central Yucca Flat

Mesozoic Granite Confining Unit **(MGCU)**
Climax stock, a Cretaceous granitic body, is exposed at the north end of Yucca Flat. The hydrologic properties of the granite differ from those of the LCA rocks into which it intruded. Based on observations at the Climax site, the granite has very low permeability and is considered to be a confining unit, though locally, fractures may contain perched water. Because of its location at the up-gradient end of Yucca Flat, this intrusive may contribute to the steep hydraulic gradient in this area.

Yucca Flat Lower Confining Unit (YF-LCU)
The Yucca Flat lower confining unit is an important HSU in the Yucca Flat region (stratigraphically similar to the TCU in Frenchman Flat) because it separates the volcanic aquifer units from the underlying regional LCA. Almost all zeolitized tuff units in Yucca Flat are grouped within the YF-LCU, which comprises mainly zeolitized bedded tuff (air-fall tuff, with minor reworked tuff). In the lower part of the section, several zeolitized nonwelded to partially welded ash-flow tuff units (e.g. Yucca Flat Tuff, Redrock Valley Tuff, tuff of Twin Peaks) are also included. Stratigraphically, the YF-LCU may include all the Tertiary volcanic strata from the top of the Paleozoic rocks to the base of the Rainier Mesa Tuff.

The YF-LCU is generally present in the eastern two-thirds of Yucca Flat. It is absent over the major structural highs, where the volcanic rocks have been removed by erosion. Areas where the YF-LCU is absent include the "Paleozoic bench" in the western portion of the basin. In northern Yucca Flat the YF-LCU tends to be confined to the structural sub-basins. Outside the sub-basins and around the edges of Yucca Flat the volcanic rocks are thinner and are not zeolitized (and thus are classified with lower Timber Mountain vitric-tuff aquifer).

The YF-LCU is saturated in much of Yucca Flat; however, measured transmissivities are very low.

Topopah Spring Aquifer (TSA)
The Topopah Spring aquifer is highly transmissive but is limited in areal extent. The TSA can be more than 100 m (332 ft) thick in southern Yucca Flat, but the unit thins to the east in the Halfpint Range, and to the south in the CP Basin and in northern Frenchman Flat. The TSA is absent west of the Topgallant fault where the volcanic strata have been eroded away. Overall, the hydraulic properties of the TSA are typical of many welded-tuff aquifers in the NTS vicinity.

Timber Mountain Hydrostratigraphic Units
The unaltered volcanic rocks of the Yucca Flat area are divided into three Timber Mountain HSUs. The hydrogeology of this part of the geologic section is complicated by the presence of one or more ash-flow tuff units that are quite variable in properties both vertically and laterally. The Timber Mountain Group includes ash-flow tuffs that might be either welded-tuff aquifers or vitric-tuff aquifers, depending on the degree of welding. In Yucca Flat these units are generally present in the central portions of the basin. They can be saturated in the deepest structural subbasins.

Alluvial Aquifer (AA)
The alluvium in Yucca Flat is similar to that described in Section 7.4. The role of the impermeable playa deposits (underlying Yucca Lake, at the southern end of Yucca Flat) may have profound hydrologic effects, especially its role in controlling recharge, but is only of local concern. Two (or more) basalt flows that have been identified within the alluvium section (Fernald *et al*., 1975) are limited in areal extent and thickness, and therefore are included in the alluvial aquifer. The alluvium thickness in the middle of the Yucca Flat basin generally ranges from about 30 m (100 ft) to just over 800 m (2,625 ft).

Because the water table is moderately deep in the Yucca Flat area, the alluvium is generally unsaturated, except in the deep structural sub-basins, or half grabens, of central Yucca Flat. These sediments are porous, and thus, have high storage coefficients. Transmissivities may also be high, particularly in the coarser, gravelly beds.

Water-level Elevation and Groundwater Flow Direction

Water-level data are abundant for Yucca Flat, as a result of more than thirty years of drilling in the area in support of the weapons testing program. However, water-level data for the surrounding areas are scarce. These data are listed in the potentiometric data package prepared for the regional model (IT 1996b; Hale *et al.*, 1995).

The SWL in the Yucca Flat basin is relatively deep, ranging in depth from about 183 m (600 ft) in extreme western Yucca Flat to more than 580 m (1,900 ft) in north-central Yucca Flat. Elevation of the water table in the Yucca Flat area varies from 1,340 m (4,400 ft) above Mean Sea Level in the north to 730 m (2,400 ft) at the southern end of Yucca Flat (Laczniak *et al.*, 1996; Hale *et al.*, 1995). Throughout much of the Yucca Flat area, the SWL typically is located within the lower portion of the volcanic section, in the Yucca Flat lower confining unit (YF-LCU). Beneath the hills surrounding Yucca Flat, the SWL can be within the Paleozoic units, while in the deeper structural subbasins of Yucca Flat, the Timber Mountain Tuff and the lower portion of the alluvium are also saturated.

Fluid levels measured in wells completed in the AA and volcanic units in the eastern two-thirds of Yucca Flat are typically about 20 m (70 ft) higher than in wells completed in the LCA (Winograd and Thordarson 1975; IT 1996b). The hydrogeology of these units suggests that the higher elevation of the water table in the overlying Tertiary rocks is related to the presence of low permeability zeolitized tuffs of the tuff confining unit (aquitard) between the Paleozoic and Tertiary aquifers. Detail water-level data indicate the existence of a groundwater trough along the axis of the valley. The semi-perched water within the AA, and volcanic aquifers eventually moves downward to the LCA in the central portion of the valley.

Water-level elevations in western Yucca Flat are also well above the regional water level. The hydrology of western Yucca Flat is influenced by the presence of the UCCU, which directly underlies the carbonate aquifer of the upper plate of the CP thrust (LCA3, locally present), AA, and volcanic rocks west of the Topgallant fault. This geometry is a contributing factor in the development of higher (semi-perched) water levels in this area. The Climax stock also bears perched water (Walker 1962; Laczniak *et al.*, 1996) well above the regional water level.

Anomalously high potentiometric head measurements noted in parts of central Yucca Flat have been related to over-pressurization of the saturated zeolitized tuffs, resulting in elevated potentiometric surfaces with increasing depth (Hawkins *et al.*, 1989; Hale 1995). This phenomenon is believed to be caused by underground nuclear tests that were conducted in this area.

The present structural interpretation for Yucca Flat depicts the LCCU at great depth, except in the northeast corner of the study area. The Zabriskie Quartzite and Wood Canyon Formation, which are both classified as clastic confining units, are exposed in the northern portion of the Halfpint Range. The high structural position of the LCCU there (and possibly in combination with the Climax stock) may be at least partially responsible for the steep hydrologic gradient observed between western Emigrant Valley and Yucca Flat.

Based on the existing data and as interpreted from the regional groundwater flow model (DOE 1997c), the overall groundwater flow direction in the Yucca Flat area is to the south and southwest (Figure 7.3). Groundwater ultimately discharges at Franklin Lake Playa to the south and Death Valley to the southwest.

PAHUTE MESA

The Western and Central Pahute Mesa CAUs, encompassing Areas 19 and 20 of the NTS, were the site of 85 underground nuclear tests (DOE 2000) (Figure 7.5). These detonations were all conducted in vertical emplacement holes (Table 7.3). The Western Pahute Mesa CAU is separated from the Central Pahute Mesa by the Boxcar fault and is distinguished by a relative abundance of tritium (IT 1999b). For hydrogeologic studies and modeling purposes, these two CAUs are treated together.

Hydrogeologically, these CAUs are considered to be part of a larger region that includes areas both within and outside the boundaries of the NTS, designated as the Pahute Mesa-Oasis Valley (PM-OV) study area. Because most of the underground nuclear tests at Pahute Mesa were conducted near or below the static water level, test-related contaminants are available for transport via a groundwater flow system that may extend to discharge areas in Oasis Valley. So, like the former testing areas of Frenchman Flat and Yucca Flat, a CAU-level hydrostratigraphic framework model is also being developed for the PM-OV area to support modeling of groundwater flow and contaminant transport for the UGTA program.

Geology Overview of Pahute Mesa

Pahute Mesa is a structurally high-volcanic plateau in the northwest portion of the NTS (Figure 7.4). This physiographic feature covers most of NTS Areas 19 and 20, which are the second most utilized testing area at the NTS. Consequently, there are numerous drill holes which provide a substantial amount of subsurface geologic and hydrologic information (Warren *et al.*, 2000). Borehole and geophysical data indicate the presence of several nested calderas which produced thick sequences of rhyolite tuffs and lavas. The older calderas are buried by ash-flow units produced from younger calderas. Most of eastern Pahute Mesa is capped by the voluminous Ammonia Tanks and Rainier Mesa ash-flow tuff units which erupted from the Timber Mountain Caldera, located immediately to the south of Pahute Mesa (Byers *et al.*, 1976). The western portion is capped by ash-flows of the Thirsty Canyon Group from the Black Mountain caldera. A typical geologic cross section for Pahute Mesa is presented in Figure 7.8. For a more detailed geologic summary, see Ferguson, *et al.*, (1994), Sawyer, *et al.*, (1994), and BN (2001a).

Underlying the Tertiary volcanic rocks (exclusive of the caldera complexes) are Paleozoic and Proterozoic sedimentary rocks consisting of dolomite, limestone, quartzite, and argillite. During Precambrian and Paleozoic time, as much as 9,600 m (31,500 ft) of these marine sediments were deposited in the NTS region (Cole 1997). For detailed stratigraphic descriptions of these rocks see Slate *et al.*, (1999).

The only occurrence of Mesozoic age rocks in this area is the Gold Meadows stock, a granitic intrusive mass located at the eastern edge of Pahute Mesa, north of Rainier Mesa (Snyder 1977; Gibbons et al.,1963).

The Silent Canyon caldera complex (SCCC) lies beneath Pahute Mesa. This complex contains the oldest known calderas within the SWNVF, and is completely buried by volcanic rocks erupted from younger nearby calderas. It was first identified from gravity observations that indicated a

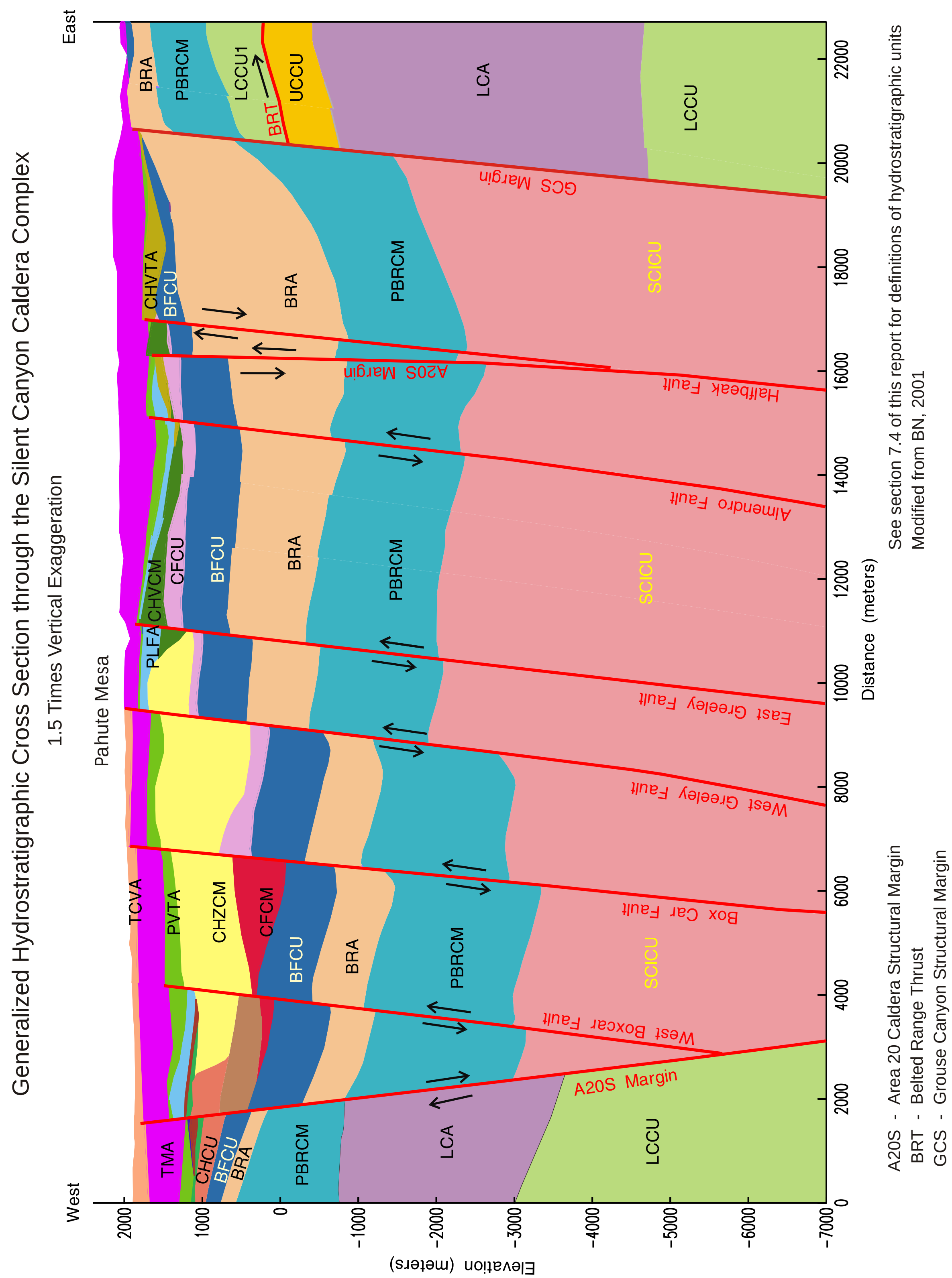

Figure 7.8 Generalized Geologic Cross Section Through Pahute Mesa

deep basin below the topographically high Pahute Mesa. Subsequent drilling on Pahute Mesa indicated that the complex consists of at least two nested calderas, the Grouse Canyon caldera and younger Area 20 caldera (13.7 and 13.25 million years old, respectively; Sawyer *et al.*, 1994). For more information on the SCCC, see Ferguson et al. (1994), which is a comprehensive study of the caldera complex based on analysis of gravity, seismic refraction, drill hole, and surface geologic data.

Like the Silent Canyon caldera complex, the Timber Mountain caldera complex (TMCC) consists of two nested calderas, the Rainier Mesa caldera and younger Ammonia Tanks caldera, 11.6 and 11.45 million years old, respectively (Sawyer *et al.*, 1994). However, unlike the SCCC, the TMCC has exceptional topographic expression, consisting of an exposed topographic margin for more than half its circumference and a well exposed central resurgent dome (Timber Mountain, the most conspicuous geologic feature in the western part of the NTS). The complex truncates the older Claim Canyon caldera (12.7 million years old; Sawyer *et al.*, 1994) in the southern portion of the model area. The calderas of the TMCC are the sources for the Rainier Mesa and Ammonia Tanks Tuffs, which form important and extensive hydrostratigraphic units at the NTS and vicinity.

The Black Mountain caldera is a relatively small caldera in the northwest portion of the Pahute Mesa area. It is the youngest caldera in the area, formed as a result of the eruption, 9.4 million years ago, of tuffs assigned to the Thirsty Canyon Group (Sawyer *et al.*, 1994).

Deep gravity lows and the demonstrated great thickness of tuffs in the Pahute Mesa area suggest the presence of older buried calderas. These calderas would pre-date the Grouse Canyon caldera and thus, could be the source of some of the pre-Belted Range units.

Hydrogeology Overview of Pahute Mesa

The general hydrogeologic framework for Pahute Mesa and vicinity was established in the early 1970s by USGS geoscientists (Blankennagel and Weir 1973; Winograd and Thordarson 1975). As described in Section 7.4, their work has provided the foundation for most subsequent hydrogeologic studies at the NTS (IT 1996a; BN 2001a).

The hydrogeology of PM-OV area is complex. The thick section of volcanic rocks comprises a wide variety of lithologies that range in hydraulic character from aquifer to aquitard. The presence of several calderas and tectonic faulting further complicate the area, placing the various lithologic units in juxtaposition, and blocking or enhancing the flow of groundwater in a variety of ways.

All the rocks in the PM-OV area can be classified as one of nine hydrogeologic units, which include the alluvial aquifer, four volcanic hydrogeologic units, two intrusive units, and two hydrogeologic units that represent the pre-Tertiary rocks (Table 7.1).

The rocks within the PM-OV area are grouped into 46 HSUs for the UGTA framework model (Table 7.6). The volcanic units are organized into 40 HSUs that include 16 aquifers, 13 confining units, and 11 composite units (comprising a mixture of hydraulically variable units). The underlying pre-Tertiary rocks are divided into six HSUs, including two aquifers and four confining units. HSUs that are common to several CAUs at the NTS are briefly discussed in Section 7.4.

The structural setting of the Pahute Mesa area is dominated by the calderas described in the previous paragraphs. Several other structural features are considered to be significant factors in the hydrology, including the Belted Range thrust fault (see Section 7.4), numerous normal faults related mainly to basin-and-range extension, and transverse faults and structural zones. However, many of these features are buried, and their presence is inferred from drilling and geophysical data.

Normal Faults
Most of the normal faults are northwest- to northeast-striking high angle faults; however, the exact locations, amount of offset along the faults, and character of the faults become increasingly uncertain with depth. Most of the normal faults in the Pahute Mesa area likely developed during and after the main phase of volcanic activity of the SWNVF (Sawyer *et al.*, 1994). Many of the faults at Pahute Mesa are believed to be syn-volcanic faults that experienced episodic movement during the various eruptive events in the area (Ferguson, et al., 1994 and Warren *et al.*, 2000). Some of the normal faults at Pahute Mesa are also caldera faults (Ferguson, *et al.*, 1994 and Warren *et al.*, 2000).

Transverse Faults and Structural Zones
Several transverse faults and structural zones have also been mapped and/or inferred through geophysical studies. These structural features include generally west to west-northwest striking high-angle faults and structural zones that are oriented transverse to generally north-striking basin-and-range normal faults. (Warren *et al*. 1985; Ferguson *et al*. 1994; Warren *et al*. 2000; Grauch *et al*. 1997, 2000, Mankinen *et al*. 1999, and Fridrich *et al*. 1999). Many of these structural features appear to be related to both caldera formation and basin-and-range extension.

Calderas
As mentioned above, calderas are hydrogeologically important features in the PM-OV area, both as sources of thicknesses of volcanic rocks, and because structures associated with them affect groundwater flow. Volcano-tectonic and geomorphic processes related to caldera development result in abrupt and dramatic changes in lithology and unit thicknesses across caldera margins. Also, the faults that form the margins themselves are probably hydrologically significant as barriers to or conduits for groundwater flow. Hydrothermal alteration, which tends to reduce hydraulic conductivity, is common around caldera complexes.

Water-level Elevation and Groundwater Flow Direction

Water-level data are relatively abundant for the former underground test area on Pahute Mesa in the northwestern portion of the NTS, as a result of more than thirty years of drilling in the area in support of the weapons testing program. However, water-level data for the outlying areas to the west and south are sparse. These data are listed in the potentiometric data package prepared for the regional model (IT 1996b), and the Pahute Mesa water table map (O'Hagan and Laczniak 1996).

The SWL at Pahute Mesa is relatively deep, at about 640 m (2,100 ft) below the ground surface. Anomalously high water levels have been encountered in several drill holes on Pahute Mesa. This water is believed to be perched (Hershey and Brikowski, 1995; O'Hagan and Laczniak, 1996). Groundwater flow at Pahute Mesa is driven by recharge in the east and subsurface inflow from the north. Local groundwater flow is influenced by the discontinuous nature of the volcanic aquifers and the resultant geometry created by overlapping caldera complexes and high angle basin and range faults (Laczniak *et al.*, 1996). Potentiometric data indicate that groundwater flow direction is to the southwest toward discharge areas in Oasis Valley and ultimately Death Valley.

RAINIER MESA

Rainier Mesa/Shoshone Mountain CAU consists of 60 CASs on Rainier Mesa and six on Shoshone Mountain, which are located in NTS Areas12 and 16 respectively (Figure 7.5). Rainier Mesa and Aqueduct Mesa form the southern extension of the northeast trending Belted Range (Figure 7.4). Together, these two mesas constitute the third major area utilized for underground testing of nuclear weapons at the NTS between 1957 and 1992. Weapons effects tests were conducted in horizontal, mined tunnels within these mesas, and two tests were conducted in vertical drill holes. Underground geologic mapping data from the numerous tunnel complexes, and lithologic and geophysical data from dozens of exploratory drill holes, provide a wealth of geologic and hydrologic information for this relatively small test area.

Geology Overview of Rainier Mesa and Shoshone Mountain

Both mesas are composed of Miocene age air-fall and ash-flow tuffs, which were erupted from nearby calderas to the west and southwest. As in Yucca Flat, these silicic volcanic tuffs were deposited unconformably on an irregular pre-Tertiary (upper Precambrian and Paleozoic) surface of sedimentary rocks (Gibbons *et al.*, 1963; Orkild 1963). The stratigraphic units and lithologies are similar to those present in the subsurface of Yucca Flat (Section 7.5). Most of Rainier Mesa and Shoshone Mountain consist of zeolitized bedded tuff, though the upper part of this section is unaltered (vitric) in some areas. At both locations, the bedded tuffs are capped by a thick layer of welded ash-flow tuff. The trace of the CP thrust fault extends through the pre-Tertiary rocks of Rainier Mesa, and several high-angle, normal faults have been mapped in the volcanic rocks at both test areas. Most of the tests in Shoshone Mountain and Rainier Mesa tunnels were conducted in the tuff confining unit, though a few were conducted in vitric bedded tuff higher in the stratigraphic section.

Hydrogeology Overview of Rainier Mesa and Shoshone Mountain

Construction of UGTA CAU-level models for the Rainier Mesa and Shoshone Mountain test areas has not yet begun. However, HGUs and HSUs in the Rainier Mesa and Shoshone Mountain area are expected to be similar to those defined for the Yucca Flat area (see Table 7.5).

Water-level Elevation and Groundwater Flow Direction

The SWL at Rainier Mesa is at a depth of about 258 m (846 ft), or about 1,847 m (6,061 ft) elevation above Mean Sea Level, and typically within the TCU. This anomalously high water level relative to the regional water level reflects the presence of water perched above the underlying tuff confining units (Walker 1962; Laczniak *et al.*, 1996). Abundant water is present in the fracture systems of some of the tunnel complexes at Rainier Mesa. This water currently is permitted to flow from U12eTunnel; however water has filled the open drifts behind barriers built near the portals of U12n and U12t Tunnels.

The water level elevation at Shoshone Mountain is not known.

Regional groundwater flow from Rainier Mesa may be directed either toward Yucca Flat or, because of the intervening UCCU, to the south toward Alkali Flat discharge area (Figure 7.3). The groundwater flow direction beneath Shoshone Mountain is probably southward as indicated in Figure 7.3.

7.6 CONCLUSION

The hydrogeology of the NTS and vicinity is complex and varied. Yet, the remote location, alluvial and volcanic geology, and deep water table of the NTS provided a favorable setting for conducting and containing underground nuclear tests. Its arid climate and its setting in a region of closed hydrographic basins also are factors in stabilizing residual surficial contamination from atmospheric testing, and are considered positive environmental attributes for existing radioactive waste management sites.

Average groundwater flow velocities at the NTS are generally slow, and flow paths to discharge areas or potential receptors (domestic and public water supply wells) are long. The water table for local aquifers in the valleys and the underlying regional carbonate aquifer are relatively flat. The zeolitic volcanic formations (TCU) separating the shallower alluvial and volcanic aquifers and the regional carbonate aquifer (LCA) appears to be a viable aquitard. Consequently, both vertical and horizontal flow velocities are low. Additionally, ^{14}C dates for water from NTS aquifers are on the order of 10,000 to 40,000 years old (Rose *et al*., 1997). Thus, there is considerable residence time in the aquifers, allowing contaminant attenuating processes such as matrix diffusion, sorbtion, and natural decay, to operate.

It is imperative that those responsible for developing viable monitoring programs understand this unique hydrogeologic setting. As described in this chapter, a vast amount of hydrogeologic data has been acquired in support of NTS programs over the last 40 years, and data continue to be acquired. Now scientists are using these data to develop and improve models for predicting groundwater flow and contaminant transport at the NTS. All of these resources, including databases, groundwater flow models, and subject matter experts, were utilized during the development of the Routine Radiological Environmenal Monitoring Program (RREMP) (DOE 1998a).

Another beneficial consequence of previous and current NTS activities is the availability of an array of boreholes that penetrate the saturated zone. A significant number of these “holes of opportunity” are in optimal locations, with appropriate well completions that provide access to aquifers of interest. Selected monitoring wells and water supply wells, both on and off the NTS, have been incorporated into a monitoring network for the RREMP. Additional wells will become available as the UGTA characterization wells are phased into the RREMP. Analytical results from routine sampling of these wells are reported in Chapter 8.0, “Groundwater Monitoring.”

Table 7.1 Hydrogeologic Units of the NTS Area

Hydrogeologic Unit	Typical Lithologies	Hydrologic Significance
Alluvial Aquifer (AA)	Unconsolidated to partially consolidated gravelly sand, eolian sand, and colluvium; thin, basalt flows of limited extent	Has characteristics of a highly conductive aquifer, but less so where lenses of clay-rich paleocolluvium or playa deposits are present.
Welded-Tuff Aquifer (WTA)	Welded ash-flow tuff; vitric to devitrified	Degree of welding greatly affects interstitial porosity (less porosity as degree of welding increases) and permeability (greater fracture permeability as degree of welding increases).
Vitric-Tuff Aquifer (VTA)	Bedded tuff; ash-fall and reworked tuff; vitric	Constitutes a volumetrically minor hydro-geologic unit. Generally does not extend far below the static water level due to tendency to become zeolitized (which drastically reduces permeability) under saturated conditions. Significant interstitial porosity (20 to 40 percent). Generally insignificant fracture permeability.
Lava-Flow Aquifer (LFA)	Rhyolite lava flows; includes flow breccias (commonly at base) and pumiceous zones (commonly at top)	Generally a caldera-filling unit. Hydrologically complex; wide range of transmissivities; fracture density and interstitial porosity differ with lithologic variations.
Tuff Confining Unit (TCU)	Zeolitized bedded tuff with interbedded, but less significant, zeolitized, nonwelded to partially welded ash-flow tuff	May be saturated but measured trans-missivities are very low. May cause accumulation of perched and/or semi-perched water in overlying units.
Intracaldera Intrusive Confining Unit (IICU)	Highly altered, highly injected/intruded country rock and granitic material	Assumed to be impermeable. Conceptually underlies each of the SWNVF calderas and Calico Hills.
Granite Confining Unit (GCU)	Granodiorite, quartz monzonite	Relatively impermeable; forms local bulbous stocks, north of Rainier Mesa and Yucca Flat; may contain perched water.
Clastic Confining Unit (CCU)	Argillite, siltstone, quartzite	Clay-rich rocks are relatively impermeable; more siliceous rocks are fractured, but with fracture porosity generally sealed due to secondary mineralization.
Carbonate Aquifer (CA)	Dolomite, limestone	Transmissivity values differ greatly and are directly dependent on fracture frequency.

Note: Adapted from Winograd and Thordarson (1975); IT (1996a); and Laczniak *et al.* (1996).

Table 7.2 Summary of Hydrologic Properties for Hydrogeologic Units at the Nevada Test Site

<table>
<tr><th colspan="3">Hydrogeologic Unit [a]</th><th>Fracture Density [b, c]</th><th>Relative Hydraulic Conductivity [c]</th><th>Hydraulic Conductivity [c, d] (meters/day) Range</th></tr>
<tr><td colspan="3">Alluvial Aquifer</td><td>Very low</td><td>Moderate to very high</td><td>0.1 - 20</td></tr>
<tr><td colspan="3">Vitric-Tuff Aquifer</td><td>Low</td><td>Low to moderate</td><td>0.1 - 1</td></tr>
<tr><td colspan="3">Welded-Tuff Aquifer</td><td>Moderate to High</td><td>Moderate to very high</td><td>1 - 30</td></tr>
<tr><td rowspan="4">Lava-Flow Aquifer [e]</td><td rowspan="2">Pumiceous Lava</td><td>Vitric</td><td>Low</td><td>Low to moderate</td><td>0.1 - 1</td></tr>
<tr><td>Zeolitic</td><td>Low</td><td>Very low</td><td>0.001 - 0.7</td></tr>
<tr><td colspan="2">Stony Lava and Vitrophyre</td><td>Moderate to high</td><td>Moderate to very high</td><td>1 - 20</td></tr>
<tr><td colspan="2">Flow Breccia</td><td>Low to Moderate</td><td>Low to moderate</td><td>0.01 - 2</td></tr>
<tr><td colspan="3">Tuff Confining Unit</td><td>Low</td><td>Very low</td><td>0.001 - 0.5</td></tr>
<tr><td colspan="3">Intrusive Confining Unit</td><td>Low to Moderate</td><td>Very Low</td><td>0.001 - 0.5</td></tr>
<tr><td colspan="3">Granite Confining Unit</td><td>Low to Moderate</td><td>Very Low</td><td>0.001 - 0.5</td></tr>
<tr><td colspan="3">Carbonate Aquifer</td><td>Low to high (variable)</td><td>Low to very high</td><td>0.01 - 20</td></tr>
<tr><td colspan="3">Clastic Confining Unit</td><td>Moderate</td><td>Very low to low [f]</td><td>0.001 - 0.2</td></tr>
</table>

(a) Refer to Table 7.1 for hydrogeologic nomenclature.

(b) Including primary (cooling joints in tuffs) and secondary (tectonic) fractures.

(c) The values presented are the authors' qualitative estimates based on data from published (IT [1996c] and Blankennagel and Weir [1973], Winograd and Thordarson [1975]) and unpublished sources (i.e., numerous Los Alamos and Lawrence Livermore National Laboratory drill-hole characterization reports).

(d) Because conductivity decreases with depth, the values corresponding to typical saturated depths are presented.

(e) Abstracted from Prothro and Drellack, 1997.

(f) Fractures tend to be sealed by the presence of secondary minerals.

Note: Adapted from Drellack and Prothro, 1997.

Table 7.3 Information Summary of Nevada Test Site Underground Nuclear Tests

Physiographic Area	NTS Area(s)	Total underground[a]		Test dates[a]	Announced high/low yield range (kiloton [kt])[a]	Depth of burial range	Overburden media	Comments
		tests	detonations					
Yucca Flat	1, 2, 3, 4, 6, 7, 8, 9, 10	659	747	1957 - 1992	zero/200 to 500	27 - 1219 m (89 - 3999 ft)	Alluvium/Playa Volcanic Tuff Paleozoic rocks	Various test types and yields; almost all were vertical emplacements above and below static water level.
Pahute Mesa	19, 20	85	85	1966 - 1992	2.3/>1000	31 - 1452 m (100 - 4765 ft)	Alluvium (thin) Volcanic tuffs & lavas	Almost all were large-diameter vertical emplacements above and below static water level; includes 19 high-yield detonations.
Rainier/ Aqueduct Mesa	12	61	62	1958 - 1992	zero/20 to 200 (most < 20)	61 - 640 m (200 - 2100 ft)	Tuffs with welded tuff caprock (little or no alluvium)	Two vertical emplacements; all others were horizontal tunnel emplacements above static water level; mostly low-yield Department of Defense weapons-effects tests.
Frenchman Flat	5, 11	10	10	1965 - 1971	< 20	179 - 296 m (587 - 971 ft)	Mostly alluvium minor volcanics	Various emplacement configurations, both above and below static water level.
Shoshone Mtn.	16	6	6	1962 - 1971	low/< 20	244 - 640 m (800 - 2100 ft)	Bedded Tuff	Tunnel-based low-yield weapons-effects and Vela Uniform tests.
Oak Spring Butte (Climax Area)	15	3	3	1962 - 1966	5.7/62	229 - 351 m (750 - 1150 ft)	Granite	Three tunnel-based tests above static water level. (HARD HAT, TINY TOT, and PILE DRIVER).
Buckboard Mesa	18	3	3	1962 - 1964	0.092/0.5	≤ 27 m (90 ft)	Basaltic Lavas	Shallow, low-yield cratering experiments (SULKY, JOHNNIE BOY[b] and DANNY BOY); all were above static water level.
Dome Mountain	30	1	5	03/12/68	five detonations @ 1.08 kt each	50 m (165 ft)	Mafic Lava	BUGGY (A, B, C, D, and E); Plowshare cratering test of five-shot horizontal salvo; all above static water level.

Note: Source: Allen, *et al.*, 1997.

(a) Source: U.S. Department of Energy (2000).

(b) JOHNNIE BOY was detonated at a depth of 1.75 ft (essentially a surface burst) approximately one mile east of Buckboard Mesa.

Table 7.4 Hydrostratigraphic Units of the Frenchman Flat Area

Hydrostratigraphic Unit (Symbol)	Dominant Hydrogeologic Unit [(a)]	Typical Lithologies
Alluvial Aquifer (AA)	AA, minor LFA	Alluvium (gravelly sand); also includes relatively thin basalt flow in northern Frenchman Flat and playa deposits in south-central part of basin.
Timber Mountain Aquifer (TMA)	WTA, VTA	Welded ash-flow tuff and related nonwelded and air-fall tuffs; vitric to devitrified.
Wahmonie Volcanic Confining Unit (WVCU)	TCU, minor LFA	Air-fall and reworked tuffs; debris and breccia flows; minor intercalated lava flows. Typically altered: zeolitic to argillic.
Tuff Confining Unit (TCU)	TCU	Zeolitic bedded tuffs, with interbedded but less significant zeolitic, nonwelded to partially welded ash-flow tuffs
Volcaniclastic Confining Unit (VCU)	TCU, Minor AA	Diverse assemblage of interbedded volcanic and sedimentary rocks including tuffs, shale, tuffaceous and argillaceous sandstones, conglomerates, minor limestones.
Upper Clastic Confining Unit (UCCU)	CCU	Argillite, quartzite
Lower Carbonate Aquifer (LCA)	CA	Dolomite and limestone
Lower Clastic Confining Unit (LCCU)	CCU	Quartzites and siltstones

(a) See Table 7.1 for descriptions of hydrogeologic units.
Note: Adapted from IT, 1998b.

Table 7.5 Hydrostratigraphic Units of the Yucca Flat Area

Hydrostratigraphic Unit (Symbol)	Dominant Hydrogeologic Units [a]	Typical Lithologies
Alluvial Aquifer (AA)	AA, minor LFA	Alluvium (gravelly sand); also includes one or more thin basalt flows, playa deposits and eolian sands
Timber Mountain Upper Vitric-Tuff Aquifer (TM-UVTA)	WTA, VTA	Includes vitric nonwelded ash-flow and bedded tuff
Timber Mountain Welded-Tuff Aquifer (TM-WTA)	WTA	Partially to densely welded ash-flow tuff; vitric to devitrified
Timber Mountain Lower Vitric-Tuff Aquifer (TM-LVTA)	VTA	Nonwelded ash-flow and bedded tuff; vitric
Yucca Flat Upper Confining Unit (YF-UCU)	TCU	Zeolitic bedded tuff
Topopah Spring Aquifer (TSA)	WTA	Welded ash-flow tuff
Belted Range Aquifer (BRA)	WTA	Welded ash-flow tuff
Belted Range Confining Unit (BRCU)	TCU	Zeolitic bedded tuffs
Pre-grouse Canyon Tuff Lava-Flow Aquifer (Pre-Tbg-LFA)	LFA	Lava flow
Tub Spring Aquifer (TUBA)	WTA	Welded ash-flow tuff
Yucca Flat Lower Confining Unit (YF-LCU)	TCU	Zeolitic bedded tuffs with interbedded but less significant zeolitic, nonwelded to partially welded ash-flow tuffs
Mesozoic Granite Confining Unit (MGCU)	GCU	Granodiorite and quartz monzonite
Upper Carbonate Aquifer (UCA)	CA	Limestone
Lower Carbonate Aquifer - Yucca Flat Upper Plate (LCA3)	CA	Limestone and dolomite
Lower Clastic Confining Unit - Yucca Flat Upper Plate (LCCU1)	CCU	Quartzite and siltstone
Upper Clastic Confining Unit (UCCU)	CCU	Argillite and quartzite
Lower Carbonate Aquifer (LCA)	CA	Dolomite and limestone
Lower Clastic Confining Unit (LCCU)	CCU	Quartzite and siltstone

(a) See Table 7.1 for description of hydrogeologic units.
Note: Adapted from Gonzales and Drellack, 1999.

Table 7.6 Hydrostratigraphic Units of the Pahute Mesa-Oasis Valley Area

Hydrostratigraphic Unit (Symbol)	Dominant Hydrogeologic Unit(s)[(a)]	Typical Lithologies
Alluvial Aquifer (AA)	AA	Alluvium (gravelly sand); also includes eolian sand
Younger Volcanic Composite Unit (YVCM)	LFA, WTA, VTA	Basalt, welded and nonwelded ash-flow tuff
Thirsty Canyon Volcanic Aquifer (TCVA)	WTA, LFA, lesser VTA	Partially to densely welded ash-flow tuff; vitric to devitrified
Detached Volcanics Composite Unit (DVCM)	WTA, LFA, TCU	Complex distribution of welded ash-flow tuff, lava, and zeolitic bedded tuff
Fortymile Canyon Composite Unit (FCCM)	LFA, TCU, lesser WTA	Lava flows and associated tuffs
Timber Mountain Composite Unit (TMCM)	TCU (altered tuffs, lavas) and unaltered WTA and lesser LFA	Densely welded ash-flow tuff; includes lava flows, and minor debris flows.
Tannenbaum Hill Lava-Flow Aquifer (THLFA)	LFA	Rhyolitic lava
Tannenbaum Hill Composite Unit (THCM)	Mostly TCU, lesser WTA	Zeolitic tuff and vitric, nonwelded to welded ash-flow tuffs
Timber Mountain Aquifer (TMA)	Mostly WTA, minor VTA	Partially to densely welded ash-flow tuff; vitric to devitrified
Subcaldera Volcanic Confining Unit (SCVCU)	TCU	Probably highly altered volcanic rocks and intruded sedimentary rocks
Fluorspar Canyon Confining Unit (FCCU)	TCU	Zeolitic bedded tuff
Windy Wash Aquifer (WWA)	LFA	Rhyolitic lava
Paintbrush Composite Unit (PCM)	WTA, LFA, TCU	Welded ash-flow tuffs, rhyolitic lava and minor associated bedded tuffs
Paintbrush Vitric-tuff Aquifer (PVTA)	VTA	Vitric, nonwelded and bedded tuff
Benham Aquifer (BA)	LFA	Rhyolitic lava
Upper Paintbrush Confining Unit (UPCU)	TCU	Zeolitic, nonwelded and bedded tuff

(a) See Table 7.1 for definitions of hydrogeologic units.

Table 7.6 (Hydrostratigraphic Units of the Pahute Mesa-Oasis Valley Area, cont.)

Hydrostratigraphic Unit (Symbol)	Dominant Hydrogeologic Unit(s)[a]	Typical Lithologies
Tiva Canyon Aquifer (TCA)	WTA	Welded ash-flow tuff
Paintbrush Lava-Flow Aquifer (PLFA)	LFA	Lava; moderately to densely welded ash-flow tuff
lower Paintbrush Confining Unit (LPCU)	TCU	Zeolitic nonwelded and bedded tuff
Topopah Spring Aquifer (TSA)	WTA	Welded ash-flow tuff
Yucca Mountain Crater Flat Composite Unit (YMCFCM)	LFA, WTA, TCU	Lava; welded ash-flow tuff; zeolitic, bedded tuff
Calico Hills Vitric-tuff Aquifer (CHVTA)	VTA	Vitric, nonwelded tuff
Calico Hills Vitric Composite Unit (CHVCM)	VTA, LFA	Partially to densely welded ash-flow tuff; vitric to devitrified
Calico Hills Zeolitized Composite Unit (CHZCM)	LFA, TCU	Rhyolitic lava and zeolitic nonwelded tuff
Calico Hills Confining Unit (CHCU)	Mostly TCU, minor LFA	Zeolitic nonwelded tuff; minor lava
Inlet aquifer (IA)	LFA	Lava
Crater Flat Composite Unit (CFCM)	Mostly LFA, intercalated with TCU	Lava and welded ash-flow tuff
Crater Flat Confining Unit (CFCU)	TCU	Zeolitic nonwelded and bedded tuff
Kearsarge Aquifer (KA)	LFA	Lava
Bullfrog Confining Unit (BCU)	TCU	Zeolitic, nonwelded tuff
Belted Range Aquifer (BRA)	LFA and WTA, with lesser TCU	Lava and welded ash-flow tuff

(a) See Table 7.1 for definitions of hydrogeologic units.

Table 7.6 (Hydrostratigraphic Units of the Pahute Mesa-Oasis Valley Area, cont.)

Hydrostratigraphic Unit (Symbol)	Dominant Hydrogeologic Unit(s)[(a)]	Typical Lithologies
Pre-Belted Range Composite Unit (PBRCM)	TCU, WTA , LFA	Zeolitic bedded tuffs with interbedded but less significant zeolitic, nonwelded to partially welded ash-flow tuffs
Black Mountain Intrusive Confining Unit (BMICU)	IICU	These units are presumed to be present beneath the calderas of the SWNVF. Their actual character is unknown, but they may be igneous intrusive rocks or older volcanic and pre-Tertiary sedimentary rocks intruded to varying degrees by igneous rocks.
Ammonia Tanks Intrusive Confining Unit (ATICU)	IICU	
Rainier Mesa Intrusive Confining Unit (RMICU)	IICU	
Claim Canyon Intrusive Confining Unit (CCICU)	IICU	
Calico Hills Intrusive Confining Unit (CHICU)	IICU	
Silent Canyon Intrusive Confining Unit (SCICU)	IICU	
Mesozoic Granite Confining Unit (MGCU)	GCU	Granodiorite and quartz monzonite
Lower Carbonate Aquifer - Thrust Plate (LCA3)	CA	Limestone and dolomite
Lower Clastic Confining Unit - Thrust Plate	CCU	Quartzite and siltstone
Upper Clastic Confining Unit (UCCU)	CCU	Argillite and quartzite
Lower Carbonate Aquifer (LCA)	CA	Dolomite and limestone
Lower Clastic Confining Unit (LCCU)	CCU	Quartzite and siltstone

(a) See Table 7.1 for definitions of hydrogeologic units.

Eleana Range (No Date Provided)